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An Infrared (IR) Emitter for a Solar Thermal System

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An Infrared (IR) Emitter for a Solar Thermal System

Luwen Jiang

Iowa State University

Research performed with Prof. Rana Biswas
and Prof. Meng Lu (ECpE) for IR experiments

M.S. (non-thesis) in Physics
Committee members: R. Biswas & J. Shinar (co-chairs), M. Wetstein, M. Lu, F. Sabzikar

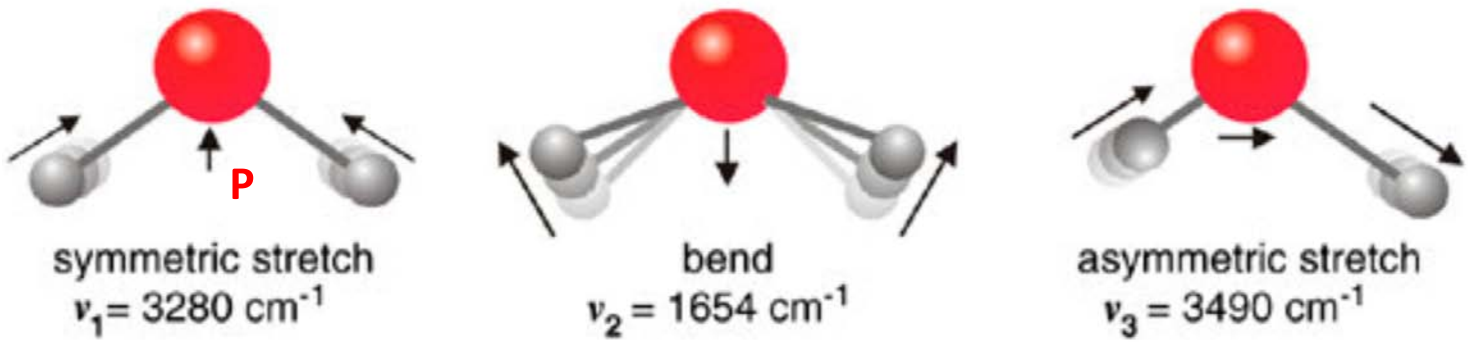
Motivation – water technologies

- Urgent need for novel water technologies
- *Large-scale* desalination of sea water needed for producing freshwater in many areas where freshwater is scarce (e.g. deserts)
- Process produced wastewaters that have very high salt concentrations, in oil-refining industry
- Potable water after hurricanes and natural disasters
- *Small-scale* applications in remote off-grid areas to produce potable water using natural water sources (military needs)

Outline

- Introduction and basic concept
- Simulations
- Experimental results
- Alternative approaches

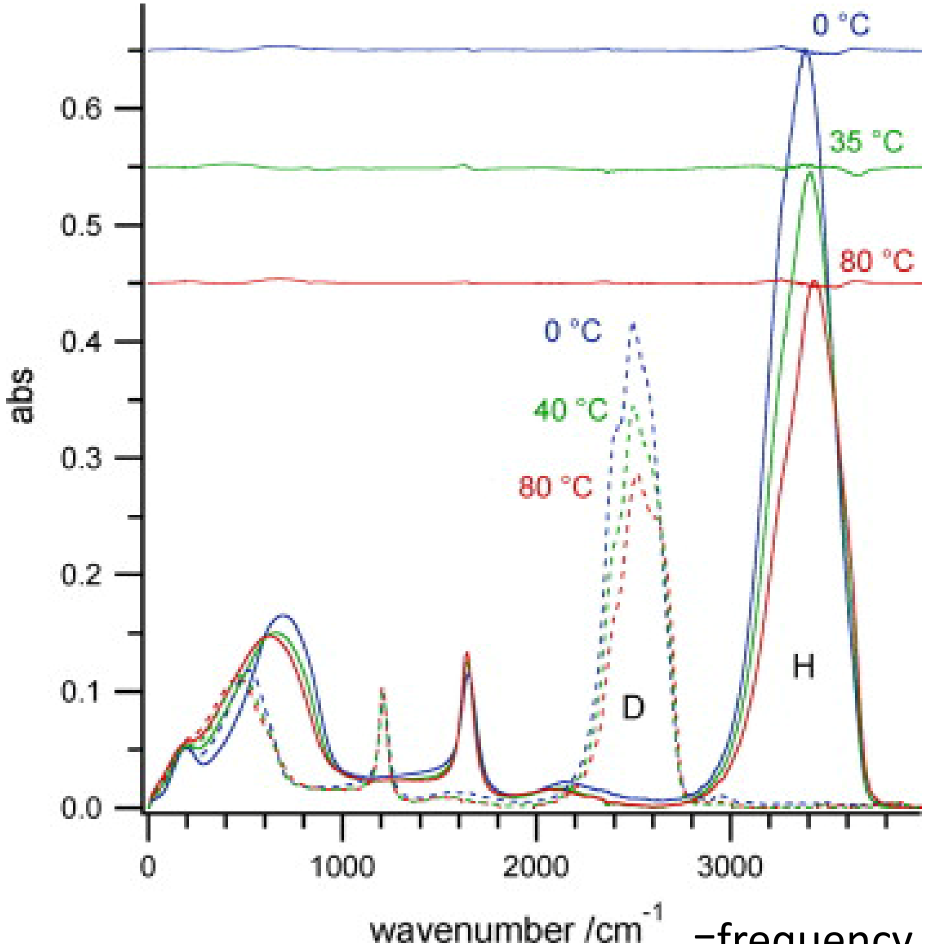
Vibrational modes of water H_2O



Wavelength (μm)	cm^{-1}	Mode
2.87	**3490**	**Asymmetric stretch, v_3**
3.05	**3277**	**Symmetric stretch, v_1**
6.08	**1645**	**Bend, v_2**

- These vibrational modes of H_2O are strongly infrared active with dipole moment **P**
- Water strongly absorbs infrared wavelengths in the 2 mid-IR bands around 3 μm and 6.1 μm

Absorption spectra of water (H_2O) and heavy water (D_2O) from up to 4000 cm^{-1} (2.5 μm)



=frequency

- Expected isotopic shift of √2 in frequencies
- Thin layer water thickness = 1 **μ**m

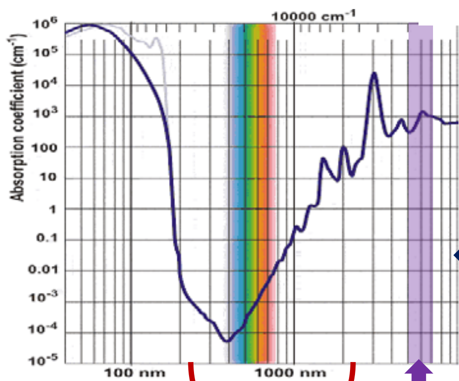
Y. Maréchal, The molecular structure of liquid water delivered by absorption spectroscopy in the whole IR region completed with thermodynamics data, *Journal of Molecular Structure*, **1004** (2011) 146-155.

Basic concept: Heat water with Spectral Concentration of Sunlight

Leverage the strong optical absorption of water in mid-IR

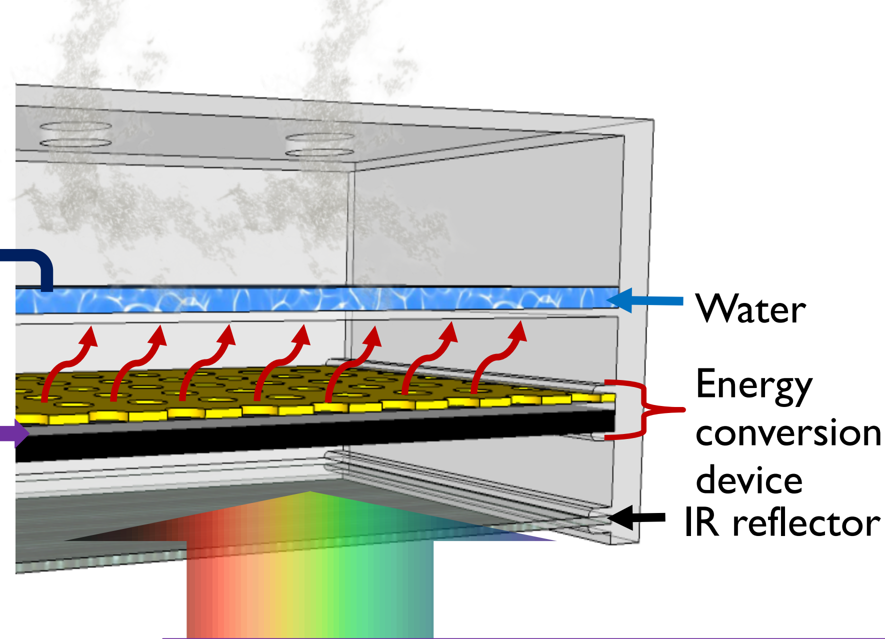
Wavelength	cm^{-1}	Mode
2.87 μm	3490	Asymmetric stretch, ν_3
3.05 μm	3277	Symmetric stretch, ν_1
6.08 μm	1645	Bend, ν_2

Water absorption spectrum

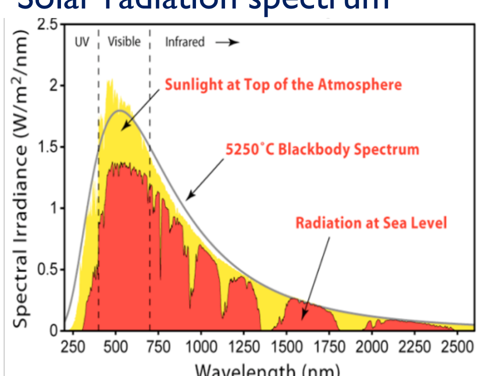


Low absorption for sun light

Wavelength conversion using thermo-plasmonic device



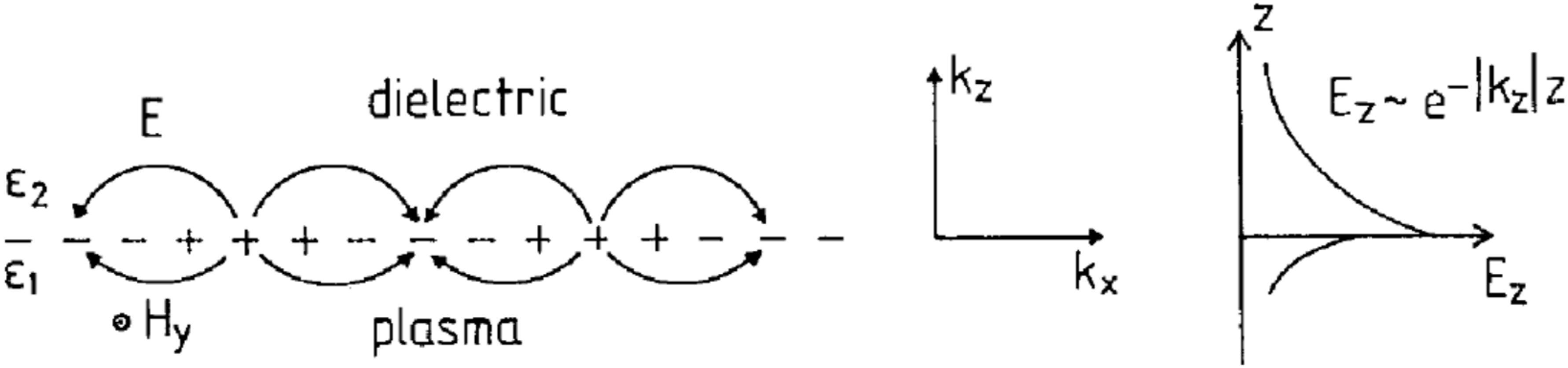
Solar radiation spectrum



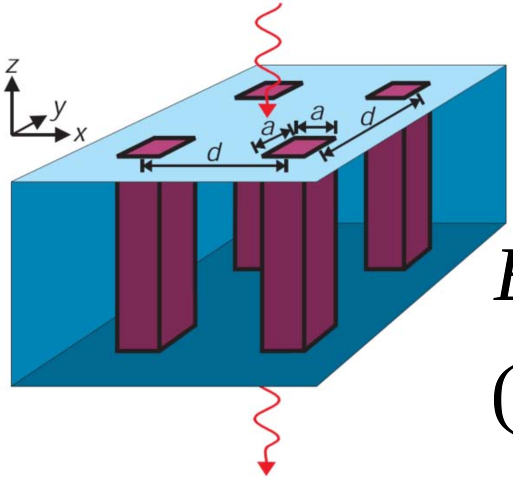
Basic Concept:
The thermo-plasmonic device absorbs sunlight
It converts the VIS-NIR sun radiation into the mid-IR emission that water absorbs strongly.

Surface plasmon (SP) on a metallic surface [1, H. Raether]

$$E = E_0 \exp[i(k_x x \pm k_z z - \omega t)], (+, z \geq 0; -, z < 0) \cdots (1)$$



Bound Surface-Plasmon-like mode induced in subwavelength holes [2, J. Pendry]

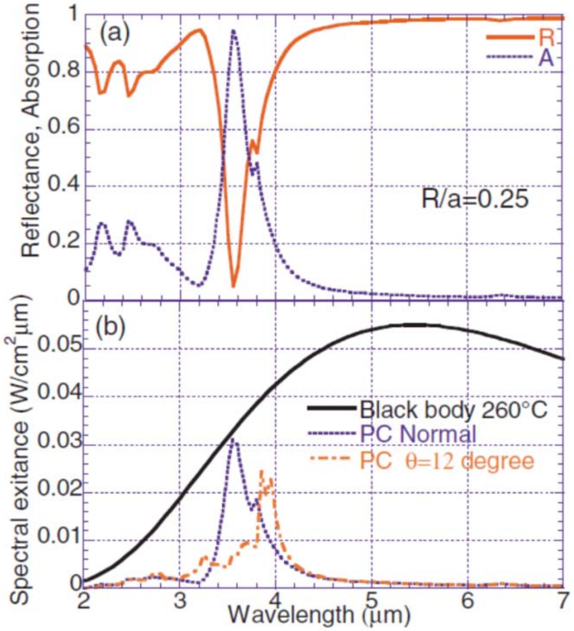


➢a×a square holes arranged on a d×d lattice are cut into the surface of a perfect conductor.

$$E = E_0[0,1,0]\sin(\pi x / a)\exp[ik_z z - i\omega t] \cdots (2)$$

$$(0 < x < a, 0 < y < a)$$

Absorption mechanisms based of subwavelength hole array on a substrate [3, 4]



➢Simulations: pitch a = 3.75 μm, radius R = 0.95 μm, R/a = 0.25.

➢Strong reflection around λ ~ 3.6 μm

$$I(d_1, \lambda, R) \propto \exp[-\frac{d_1}{l_d}] \cdots (3)$$

$$\frac{1}{l_d} = 2\sqrt{(\frac{k_{nr}}{R})^2 - (\frac{2\pi}{\lambda})^2} \cdots (4)$$

where d_1 is the depth of holes, l_d is a decay length and k_{nr} is the r-th zero of the n-th Bessel function.

➢A = 1 – R_{tot} – T_{tot} ≅ 1 - R_{tot} (T~0)

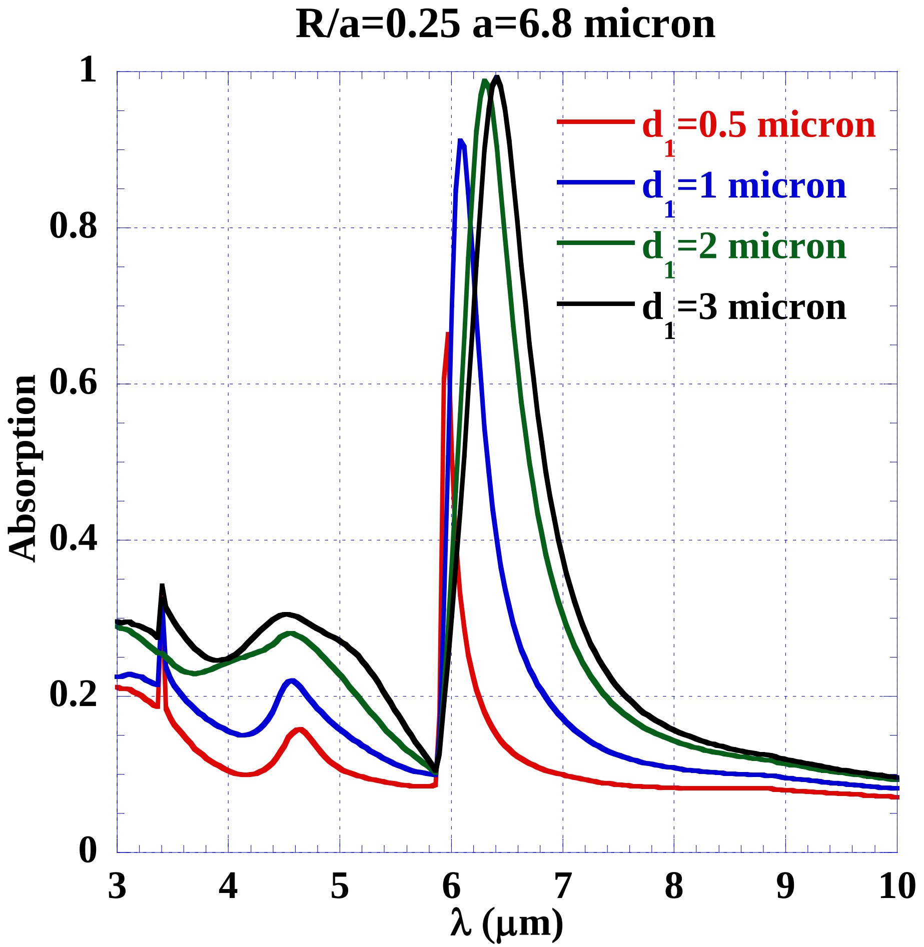
➢λ ~ 3.6 μm, d_1 ≈ 1.88 μm >> l_d ≈ 0.56 μm, so the holes are deep enough to dissipate energy from the incident wave.

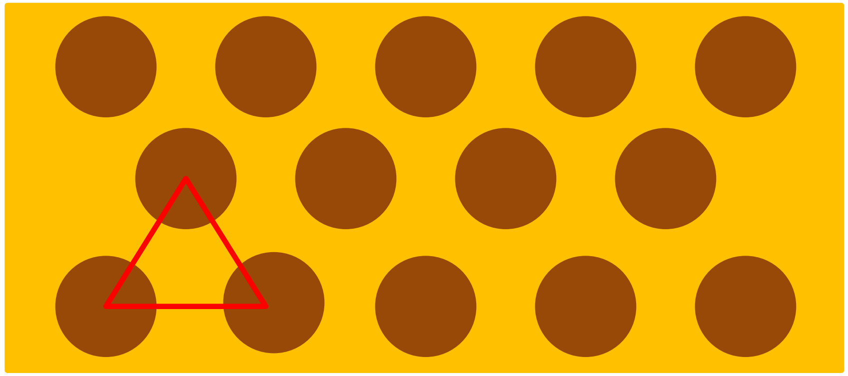
➢When this structure is heated, it emits at this resonant wavelength with the emission given by the black-body spectrum mutiplied by the absorption

➢R_{tot} includes diffraction

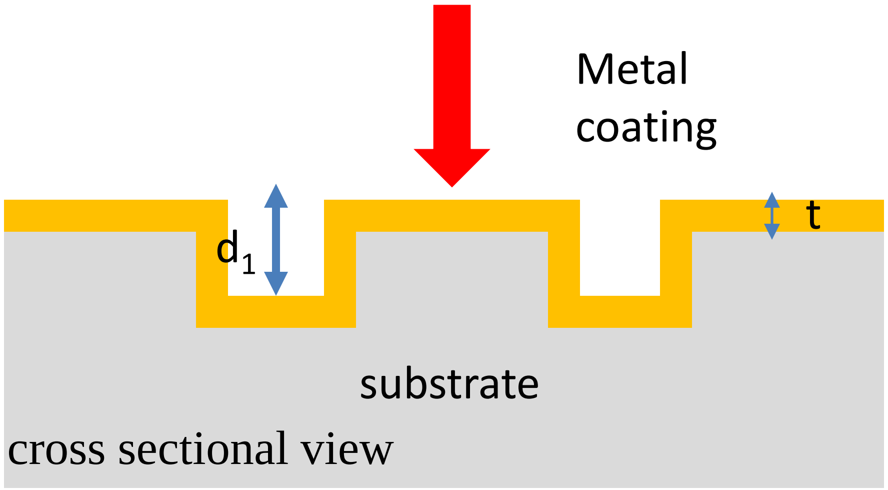
Simulations

Vary depth





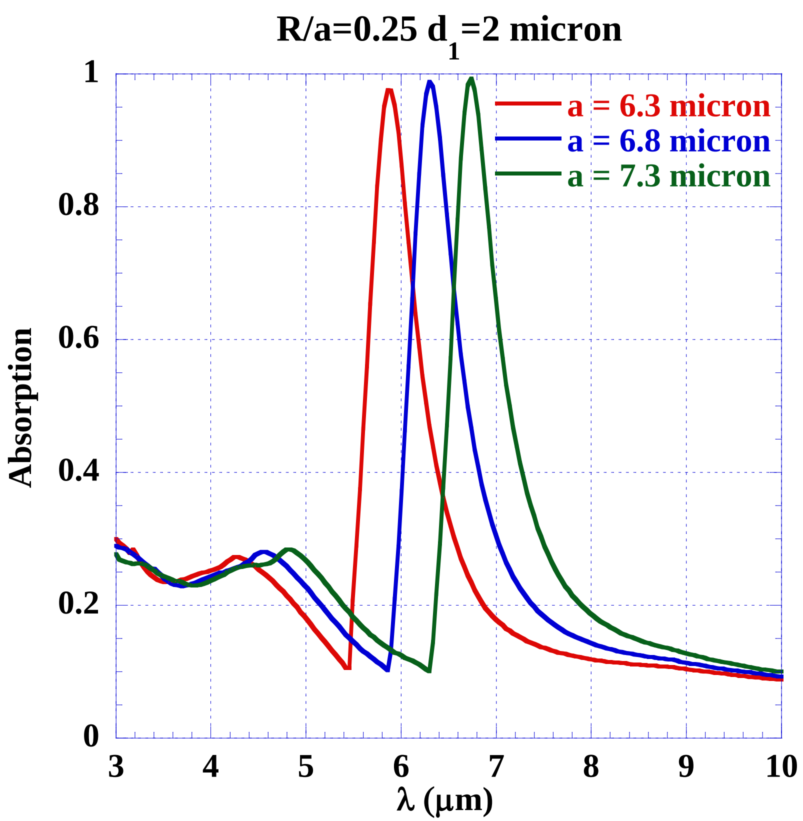
- top view
- Triangular lattice of holes



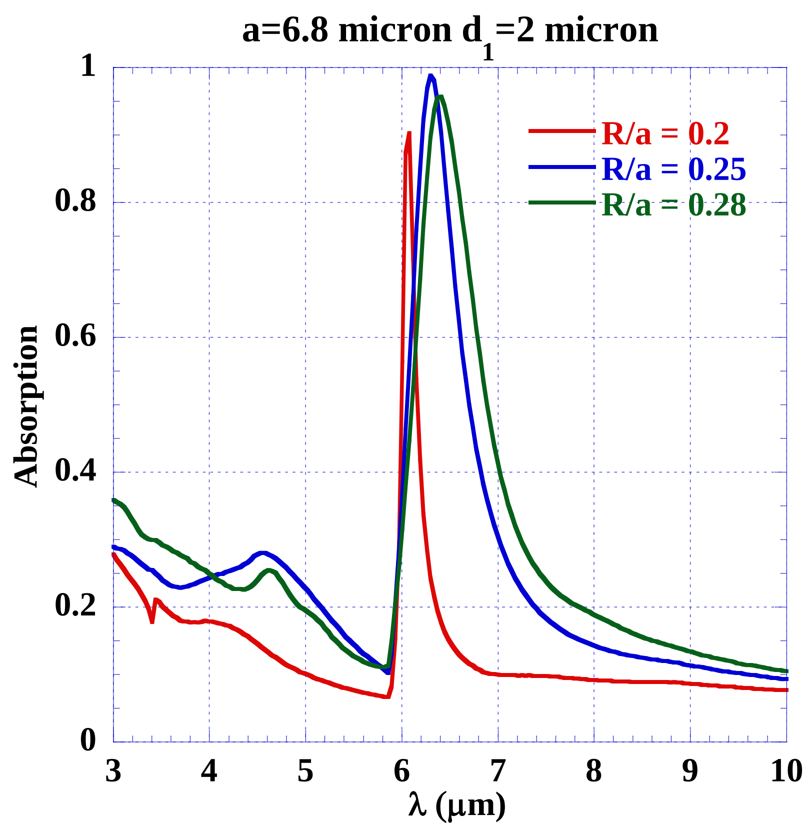
- Metal thickness t > skin depth – may model by a bulk metal sheet with indentations
- Fix pitch a=6.8 μm ; vary depth of holes
- Strong absorption (~100%) between 6- 6.5 μm
- Can be easily fabricated by photolithography in Si wafer followed by metal deposition

- depth of the holes changed from 0.5 to 3 microns, the peak shifts from 6 to 6.4 microns
- full width at half maximum (FWHM) increased significantly.

Vary pitch *a*



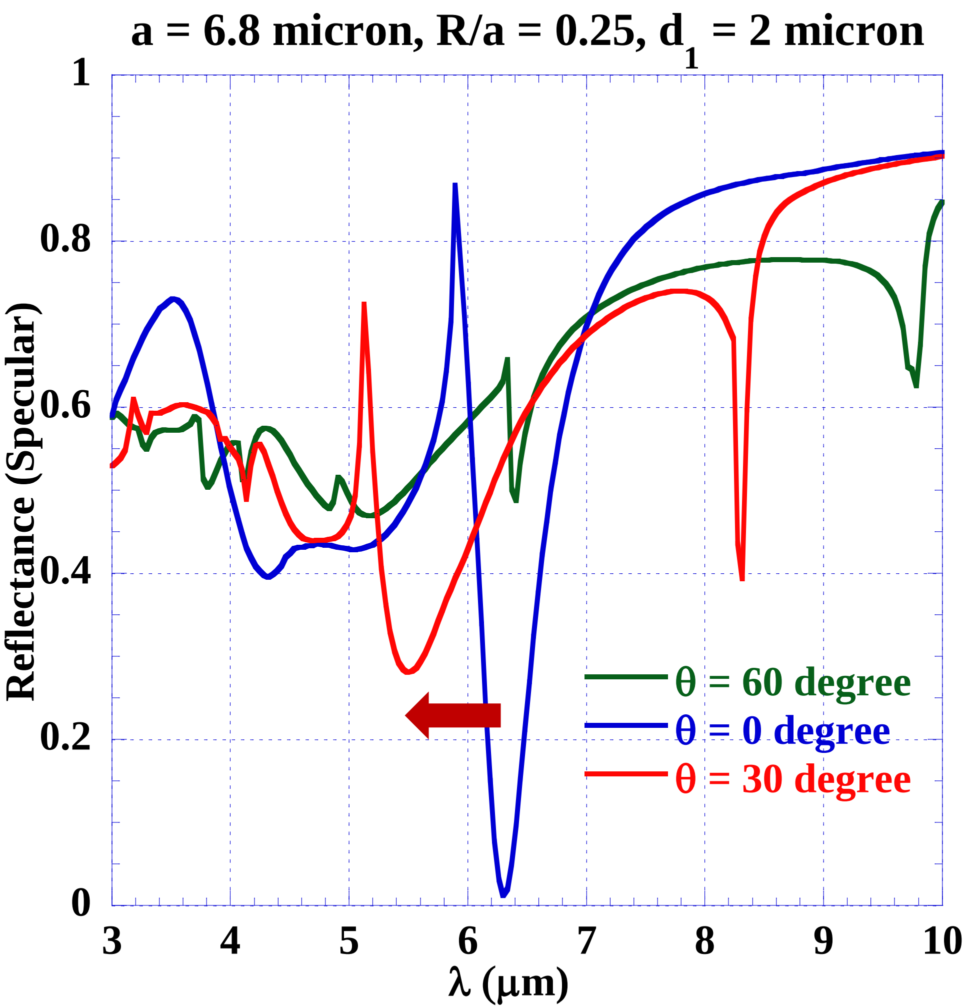
Vary the ratio R/a (radius by pitch)

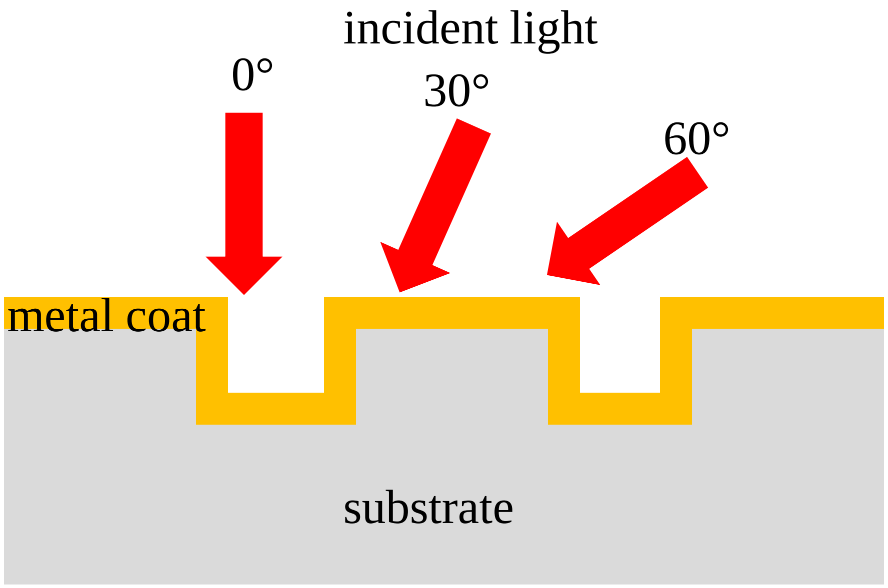


- Left figure: fix depth d_1 = 2 μm ; R/a = 0.25; vary pitch of holes
- Strong absorption peak (~100%) scales with the pitch a of the array
- When the pitch a changed from 6.3 to 7.3 μm, the peak shifted to longer wavelength

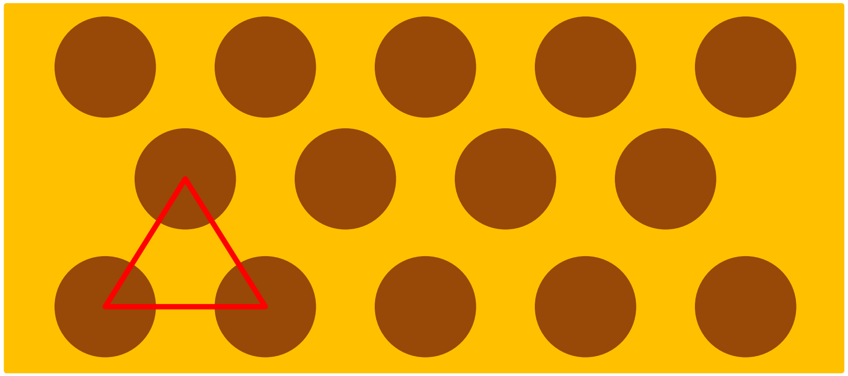
- Right figure: fix depth d_1= 2 μm ; pitch a=6.8 μm ; vary radius of holes
- Position of absorption peak (~90-100%) scales with the pitch a of the array

Vary angle of the incident light





cross sectional view



triangular lattice periodicity.

➢Simulated specular reflection

➢the angle of incident light became 30° from 0°, meanwhile the main reflectance dip shifts to the range between 5 to 6 microns.

Thermal emission

Spectral radiance of a black body based on Plank's law

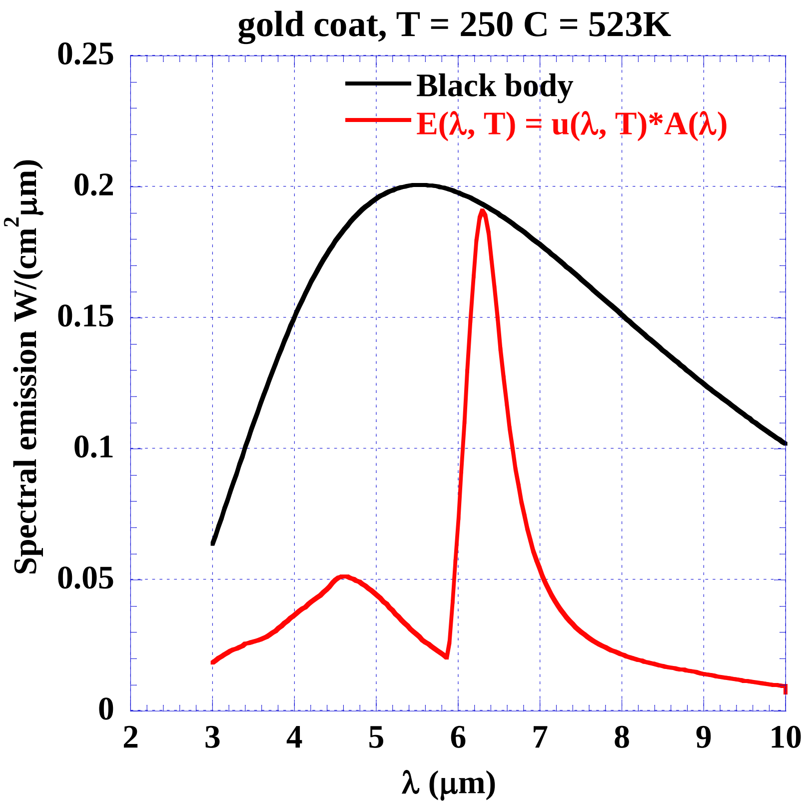
$$B(\lambda, T) = \frac{2hc^2}{\lambda^5} \frac{1}{e^{\frac{hc}{\lambda k_B T}} - 1} \cdots (5)$$

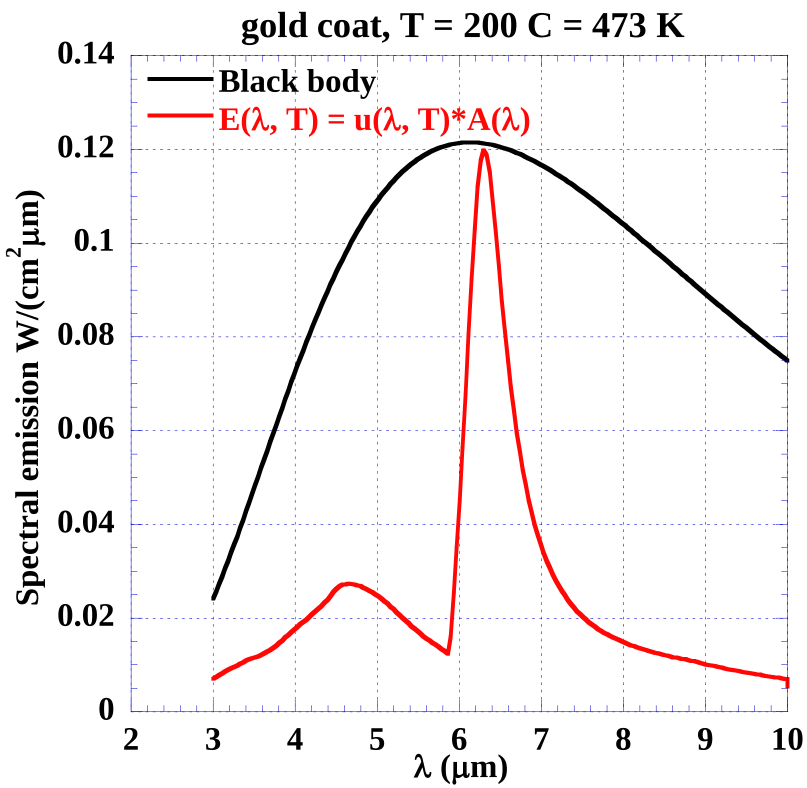
Spectral emission based on Kirchhoff's law of thermal radiation

$$E(\lambda, T) = B(\lambda, T) A(\lambda) \cdots (6$$

Thermal emission (simulated)

Spectral emission of the pattern with gold coat at T = 523 K, 473K



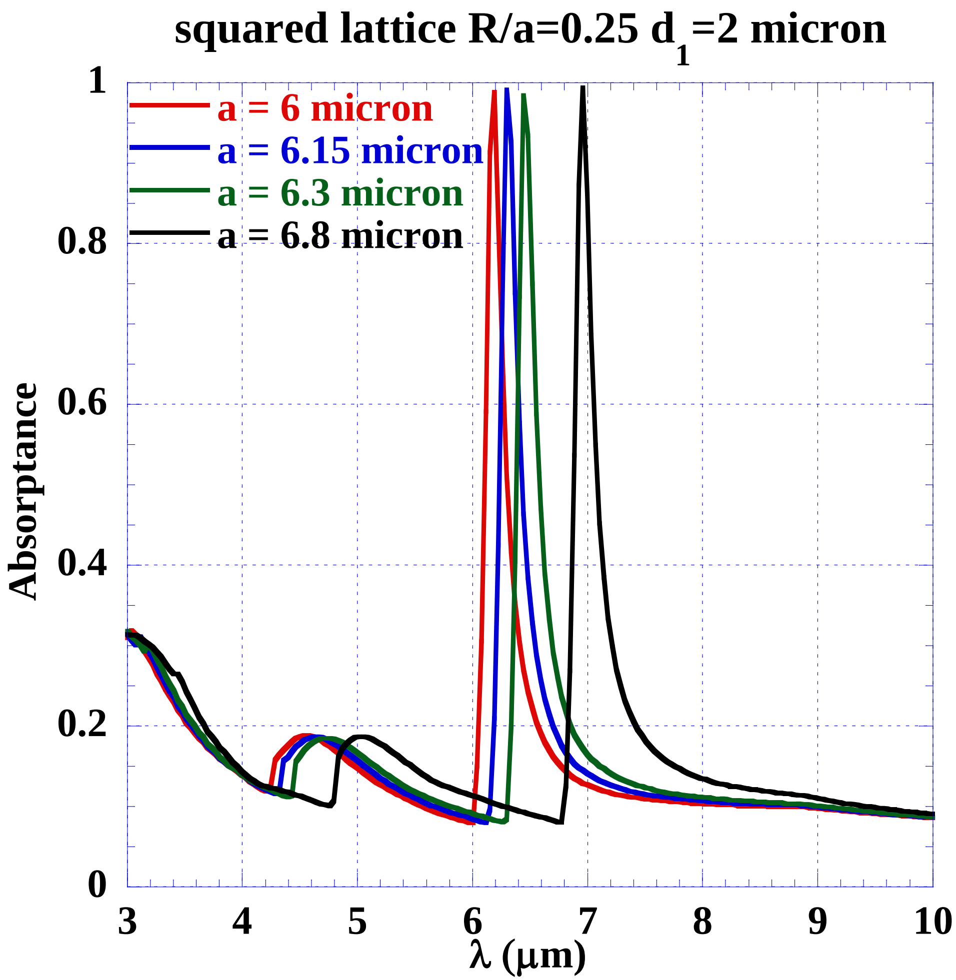


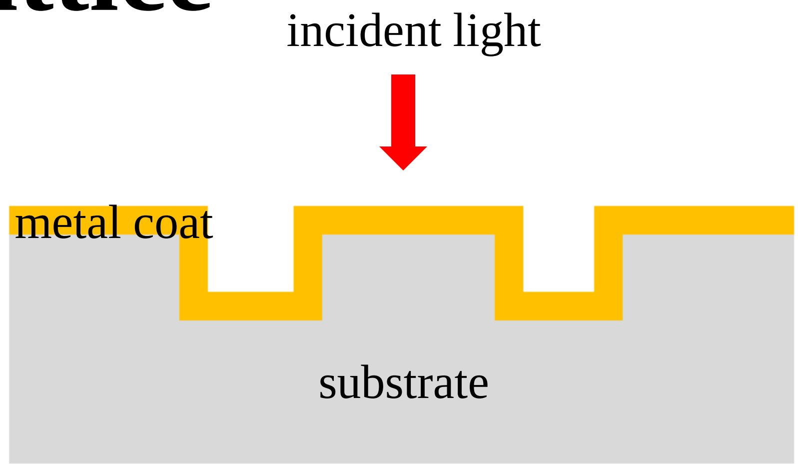
- Simulated spectral emission at 200°C and 250°C, compared to the blackbody.
- The peak of simulated spectral emittance is at 6.3 micron. It is very high, almost reaching the blackbody curve.

➢Convert broad band visible and near IR light from solar – to heat substrate- that emits in narrow infrared band

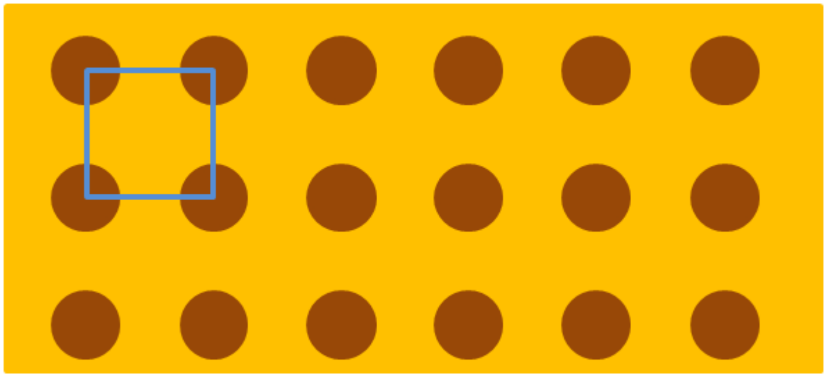
➢Wavelength conversion

Square lattice





cross sectional view



rectangular lattice periodicity

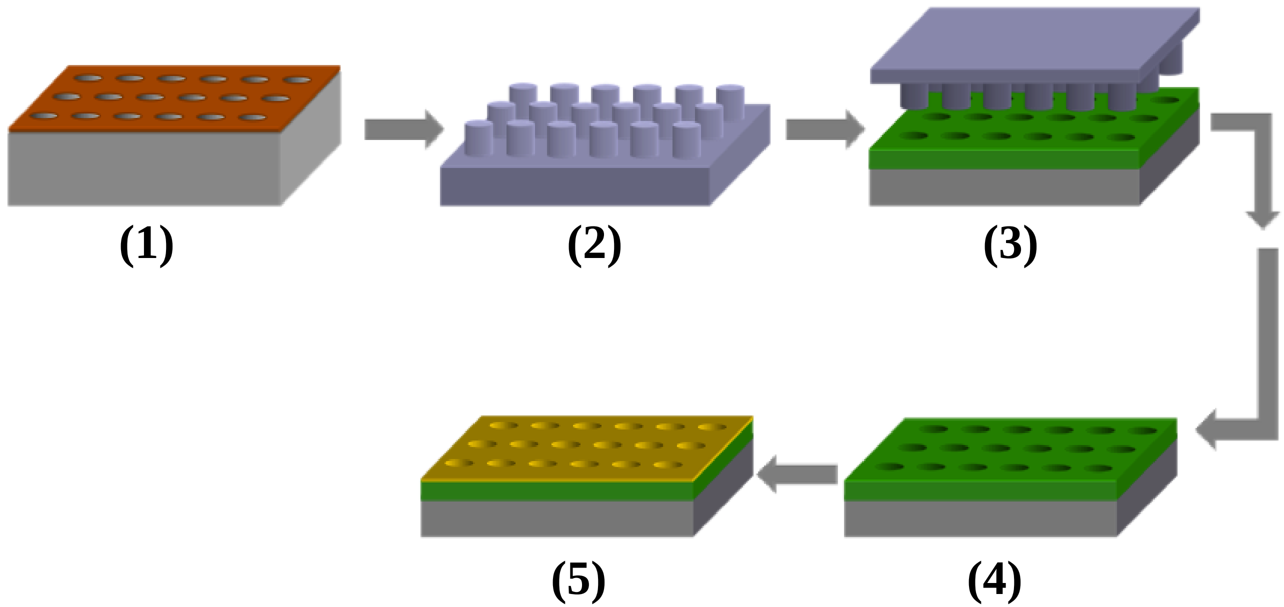
➢simulated absorption of the pattern with gold coat.

➢pitch changed from 6 to 6.8 microns, the peak shifted to longer wavelength.

Experimental results

Fabrication

➢Si Wafer -> PDMS (Polydimethylsiloxane) -> NOA 85 (substrate) on PET (Polyethylene terephthalate) -> Gold Coating



➢decided the pitch, R/a and depths of holes of the pattern and ordered the etched Si wafers (1) from Minnesota Nano Center

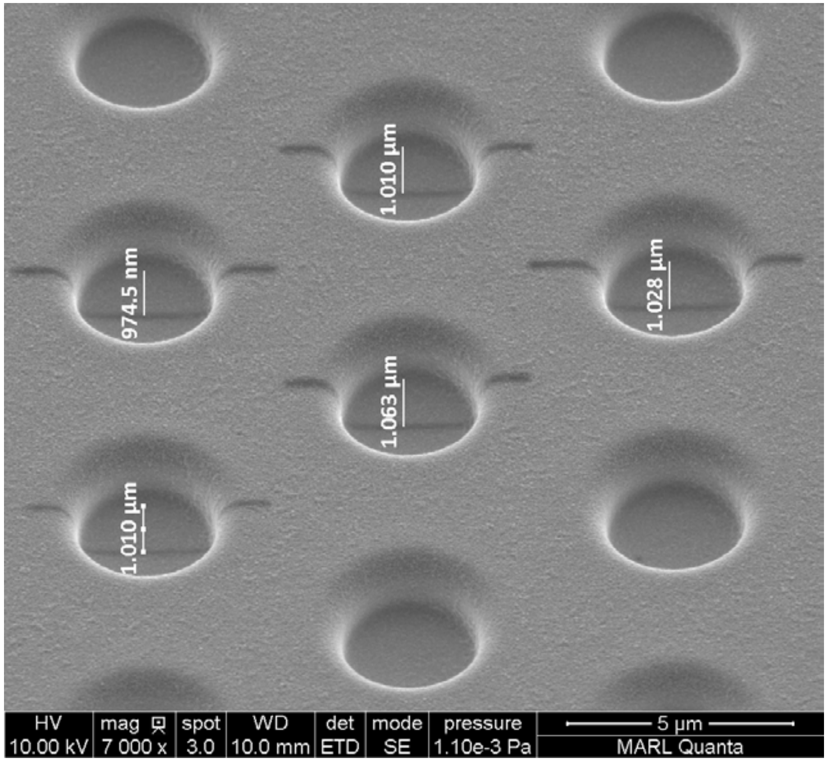
➢used PDMS (2, purple) to replicate the pattern on wafers

➢NOA 85 (3, green) is liquid initially. By UV imprint, on a PET (3, grey) film, it became solid and replicated the pattern from PDMS

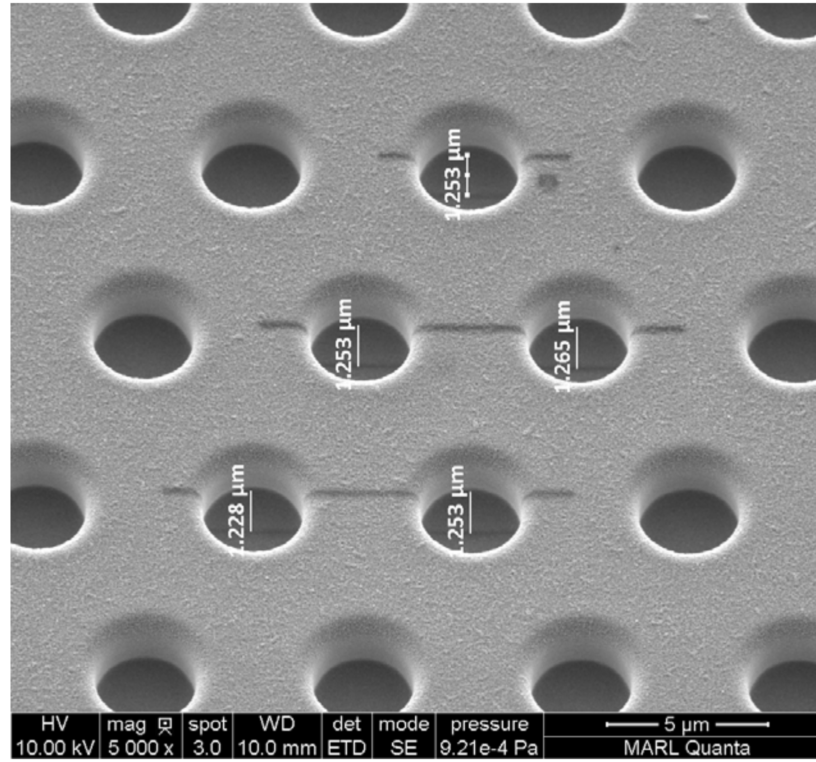
➢patterned solid NOA 85 can be used as substrate and coated with gold layer (5, gold) by sputtering coater

SEM at MARL to show the depth of holes

➢ϕ is the angle between the SEM stage plane and horizontal plane.



➢ϕ is 45°, so the depth of sample 1 is about 1.4 µm.

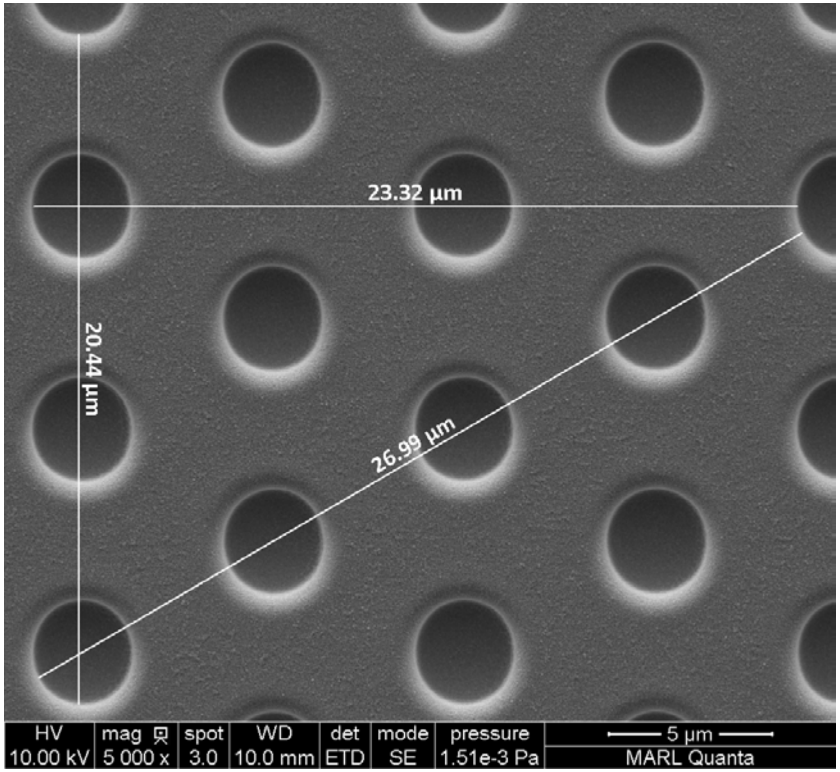


➢ϕ is 30°, so the depth of sample 5 is about 2.5 µm.

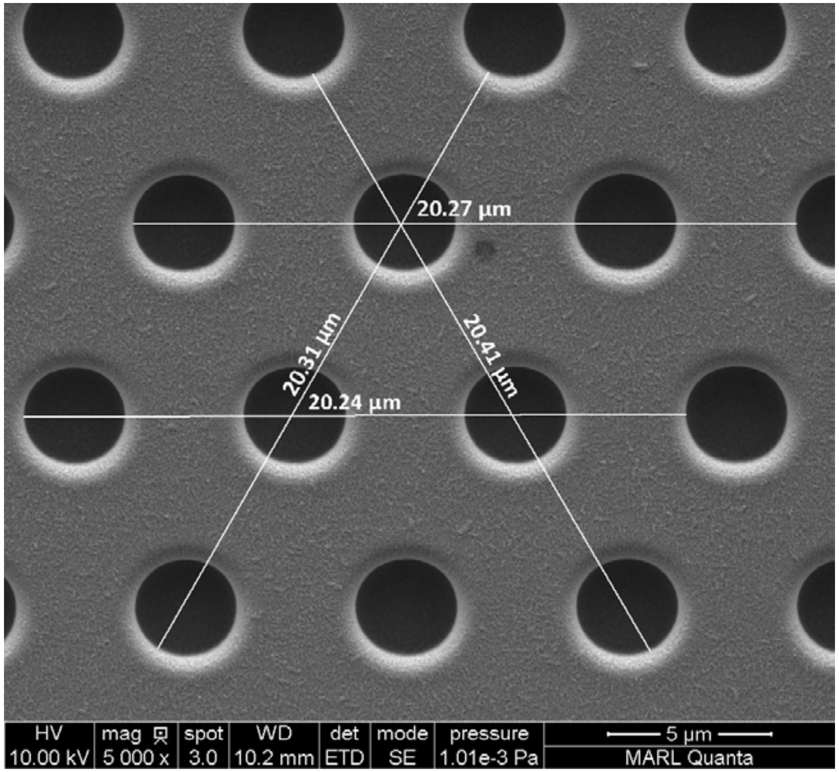
➢the coat thickness will be ~ 50 nm if sputtering coating lasts for 4 min, based on the standard calibration by SEM

➢every single sample takes ~12 min, so the thickness should be ~ 150 nm

SEM at MARL to show the pitch of holes



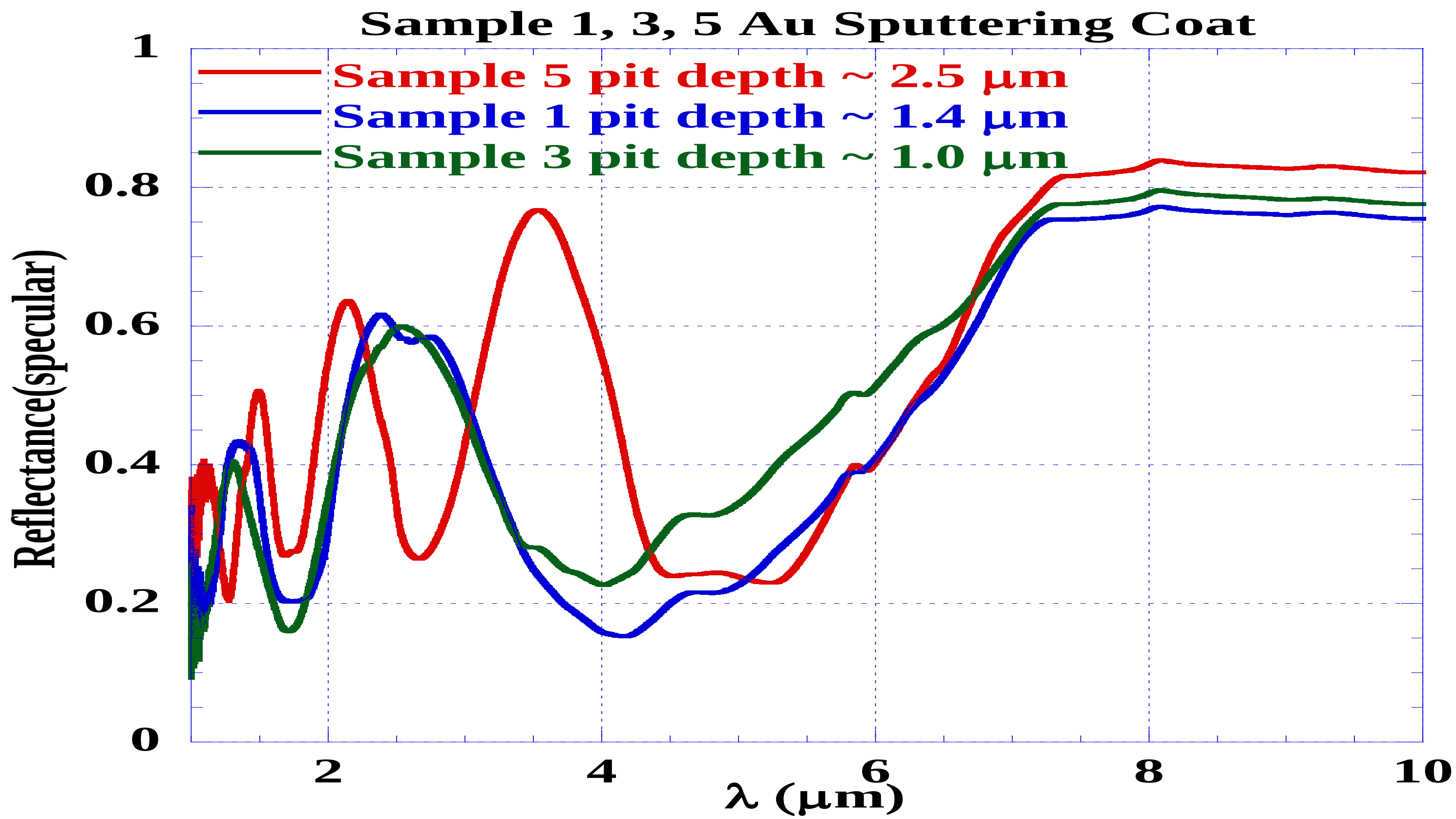
Sample 1, the depth of holes is 1.4 microns.



Sample 5, the depth of holes is 2.5 microns.

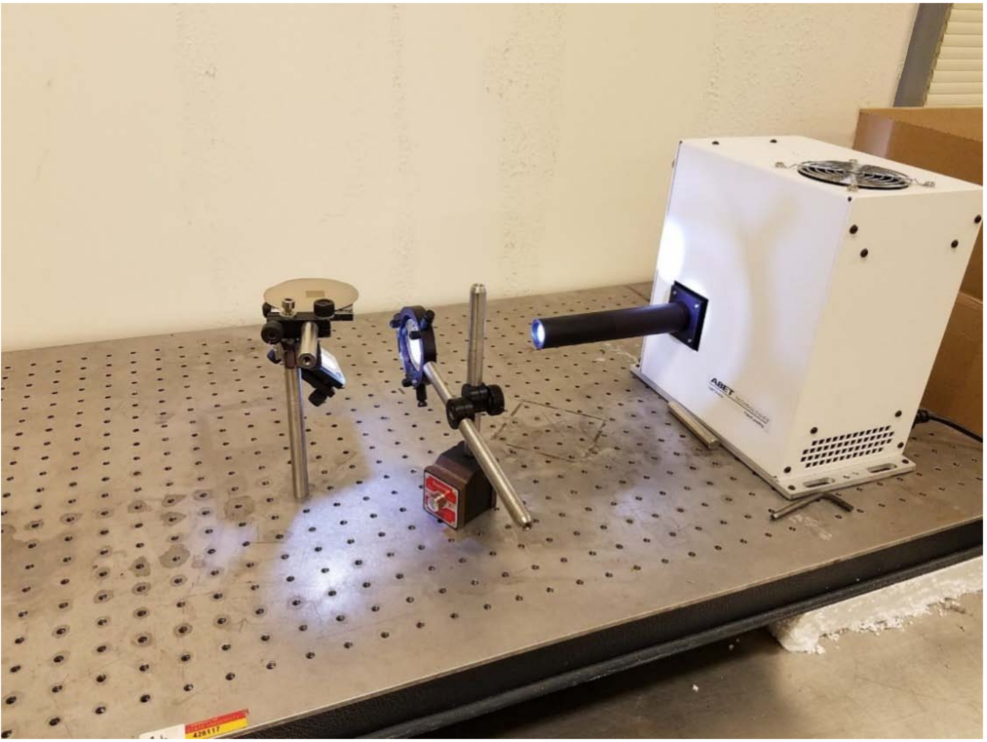
The two figures above indicate that the pitch is about 6.8 µm, which matches our simulations.

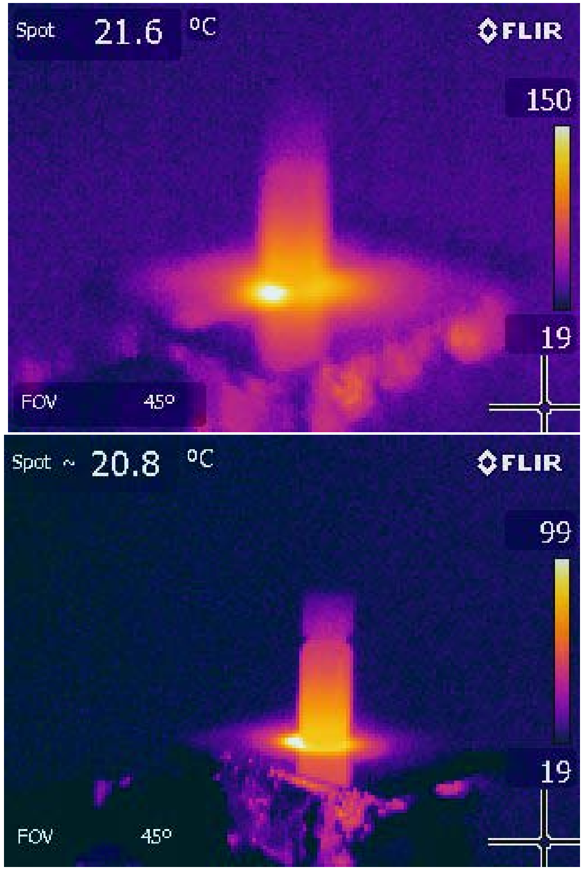
Experiments by FTIR



- ➢reflectance of the patterned films with gold sputtering coat by FTIR
- ➢hole depth varies from 1 to 2.5 microns
- ➢main dip of the sample 5 is at the range from 4 to 6 microns

Demonstration of water heating





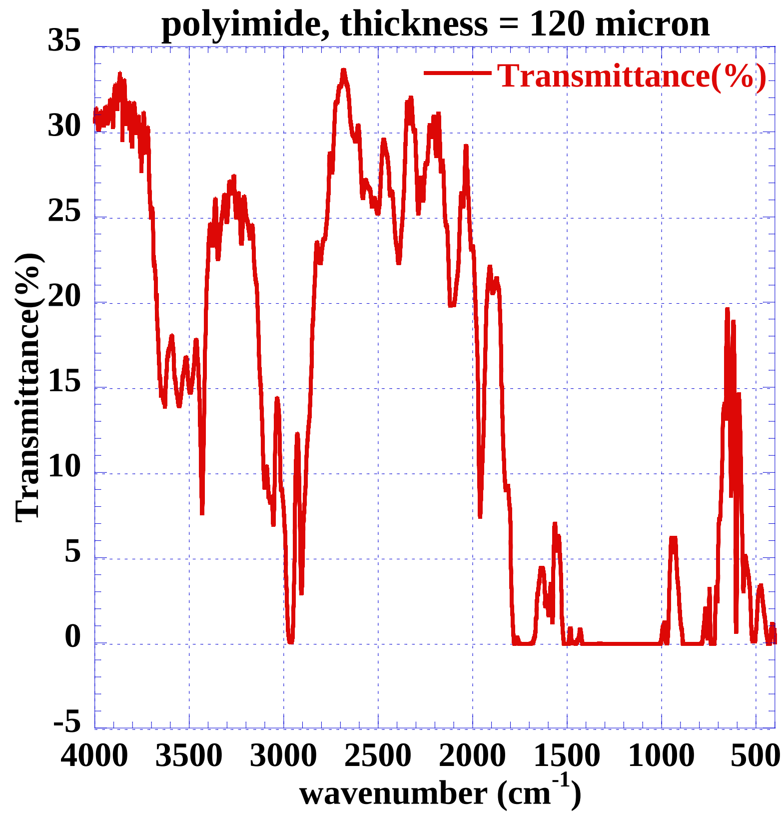
- Setup test bench to measure heating of water (at MRC)
- Solar concentrator focused onto back of plasmonic emitter – backside coated with Carbon-black
- Vial of water on plasmonic emitter monitored with IR camera
- The temperature of heating water can reach > 90°C after few minutes of solar illumination
- Observed water boiling

Alternative approaches

Transmittance of a polyimide film

➢The temperature polyimide can stand is up to 400 °C, so it won't deformed while working at higher temperature.

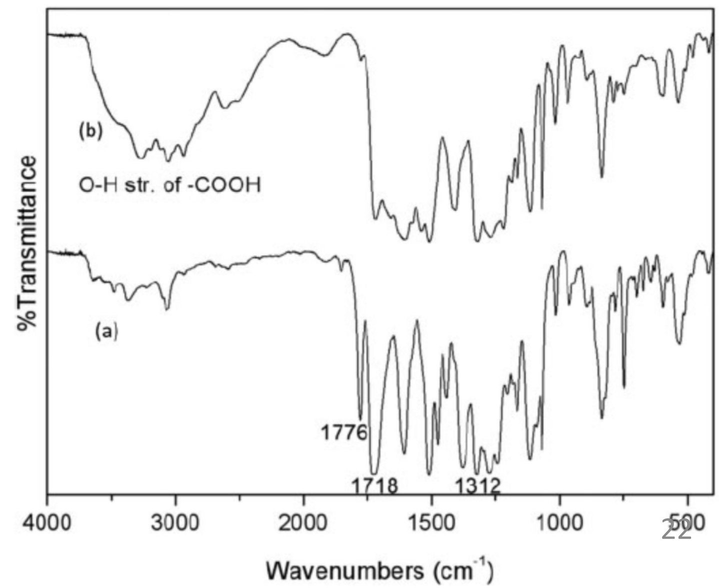
➢The figure below shows transmittance of a polyimide film, of thickness 70 microns. The transmittance at the range from 1000 to 1776 cm^{-1} (5.6 to 10 microns) is very low. The absorption is due to C=O stretch (1754 - 1667 cm^{-1}), CH2, CH bend; C=C stretch mainly.



➢In the figure above, when the thickness became 120 microns, the transmittance became almost 0 by FTIR measurement.

➢Absorptance = 1 - Transmittance
because the reflectance is ~ 0 in our FTIR measurement

➢We can use polyimide film with carbon absorber to convert solar energy to IR radiation.

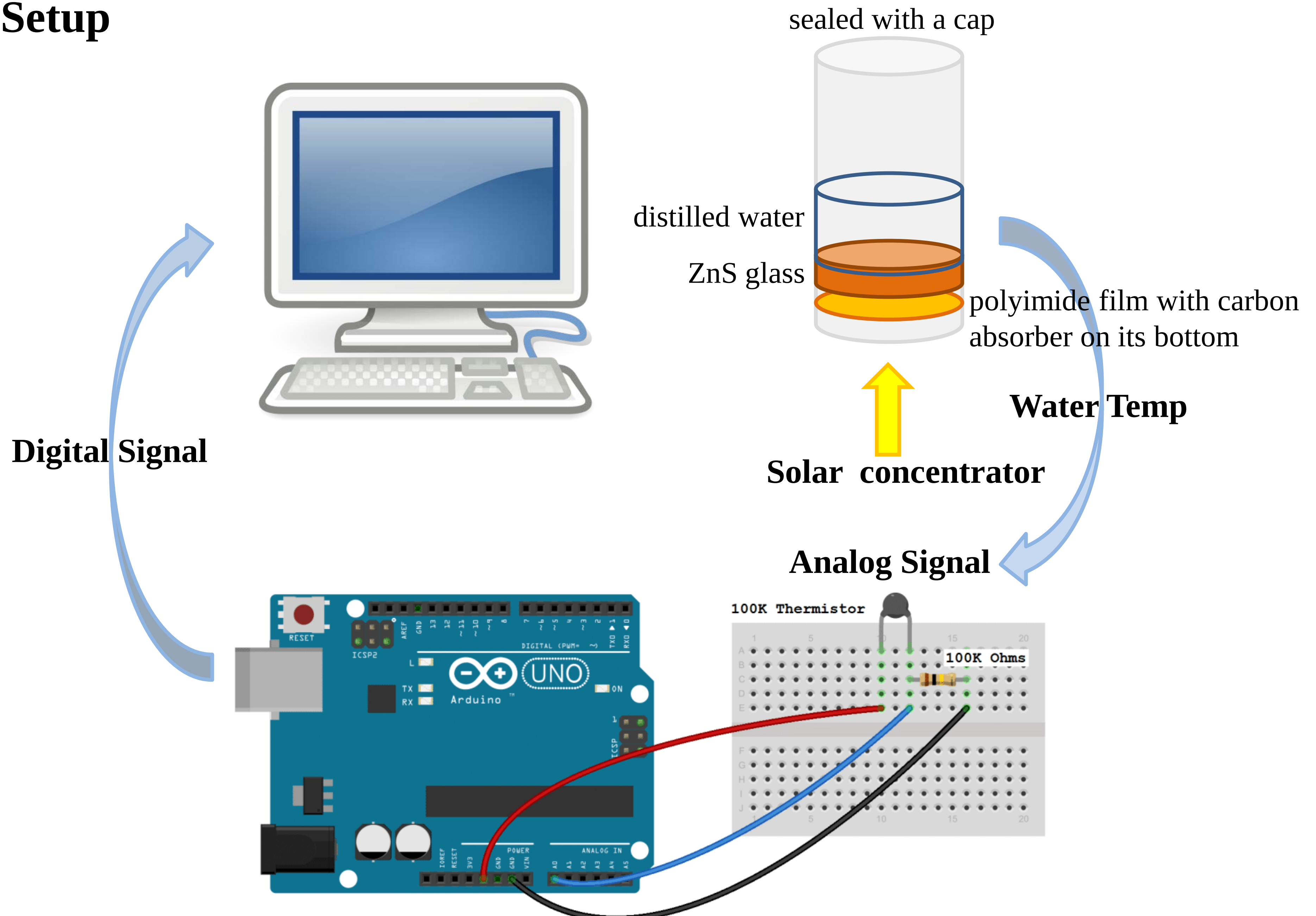


Synthesis and properties of electroactive aromatic polyimides with methyl- or trifluoromethyl-protecting triphenylamine units

High Performance polymers Volume: 29 issue: 5, 544-555 (2017)

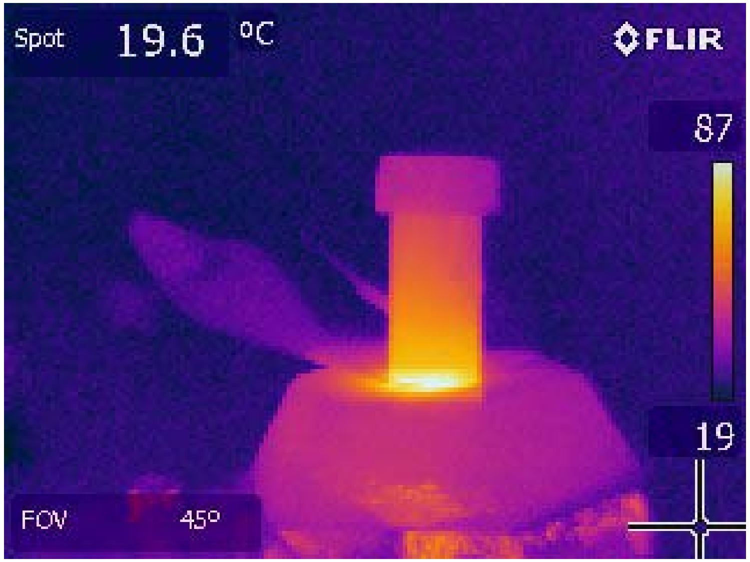
Sheng-Huei Hsiao[1] and Kai-Han Lin[2]

Setup



sealed with a cap
distilled water
ZnS glass
polyimide film with carbon absorber on its bottom
Water Temp
Solar concentrator
Digital Signal
Analog Signal
100K Thermistor
100K Ohms
UNO
Arduino

Water heating with polyimide



- Solar concentrator focused onto back of polyimide – coated with Carbon black
- Vial of water on substrate monitored with IR camera
- The temperature of heating water can reach 50°C ~ 80°C after about one hour

Future work

- We will redesign the parameters of the pattern in order to shift the absorption peak of the IR emitter to ~ 3.1 microns. There's a more significant absorption peak of water.
- With our partner – Microcontinuum Inc. (Cambridge, MA) we will try to fabricate the pattern on a metallic foils directly without any polymer in order to keep the IR emitter working at higher temperature.

References

[1] H. Raether, Surface Plasmons on Smooth and Rough Surfaces and on Gratings.

[2] J. Pendry, L. Martin-Moreno, and F. J. Garcia-Vidal, Science **305**, **847**, (2004).

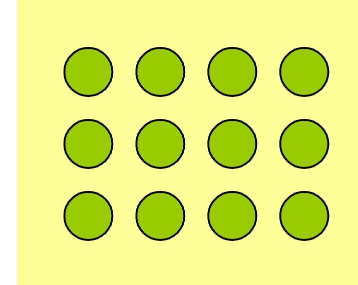
[3] L. Degiron, H. J. Lezec, W. Barnes, and T. W. Ebbesen, Appl. Phys. Lett. **81, 4327** (2002).

[4] R. Biswas, D. Zhou, I. Puscasu, E. Johnson, A. Taylor, and W. Zhao, Appl. Phys. Lett. **93**, **063307** (2008).

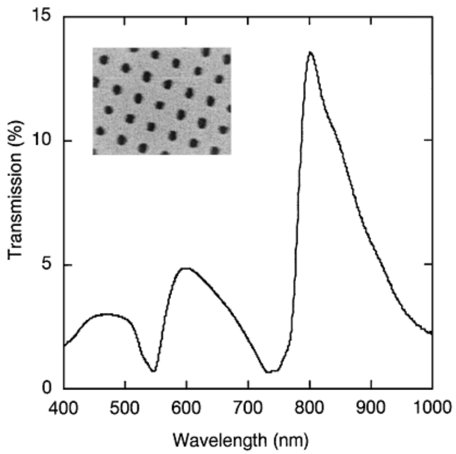
Thanks

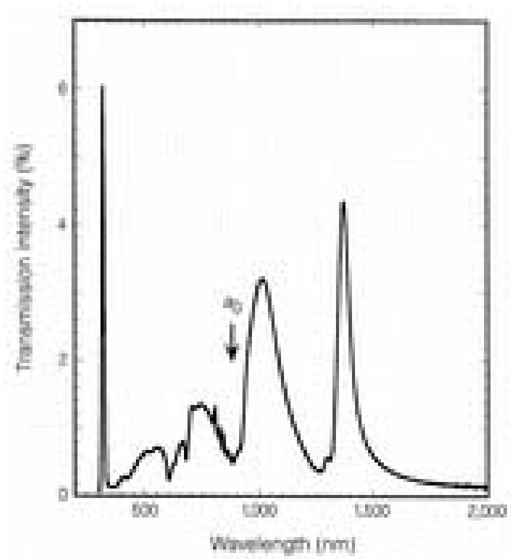
Backups

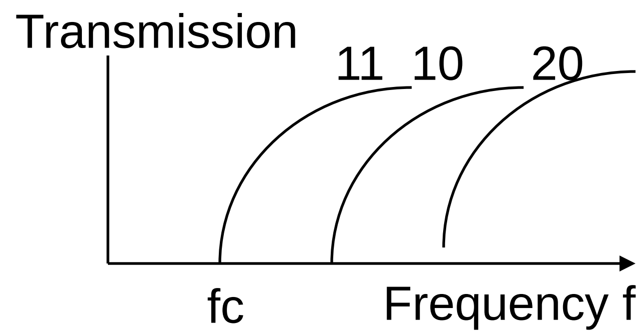
Enhanced transmission through subwavelength hole arrays



a=750nm







- Ebbesen, Lezec, Ghaemi, Thio, Wolff -Nature **391**, 667 (1998)
- Extraordinary transmission peak at λ>a and λ ~na (substrate)
- Large enhancement over classical transmission expected for area of holes $I/(I_0{*}\pi r^2/a^2)$
- Waveguide TE(11) mode transmits at $\lambda c = 3.42$ R
- Sub-wavelength regime- waveguide cutoff $\lambda c < d < \lambda$ (no WG modes in small holes)
- Resonant excitation of surface plasmons on both sides of the film vs diffraction of light through holes ?
- Explosion of interest in sub-wavelength arrays: imaging, NSOM, lithography

Simulations: Scattering-matrix method

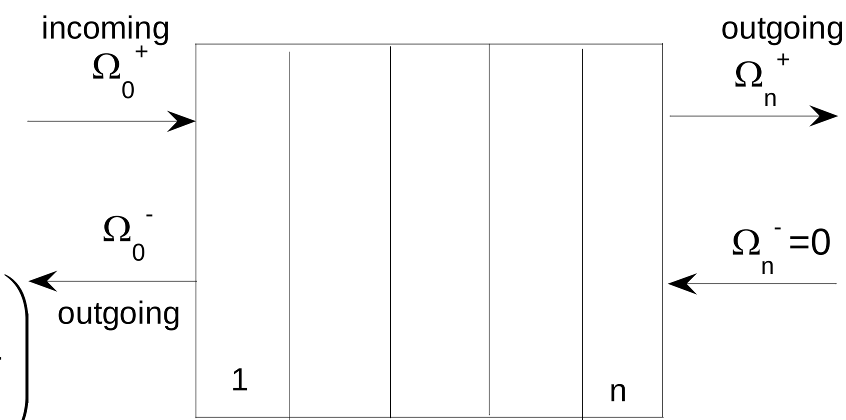
$$\nabla \times E = -\frac{1}{c}\frac{\partial H}{\partial t}; \nabla \times H = \frac{\varepsilon(r)}{c}\frac{\partial E}{\partial t}$$

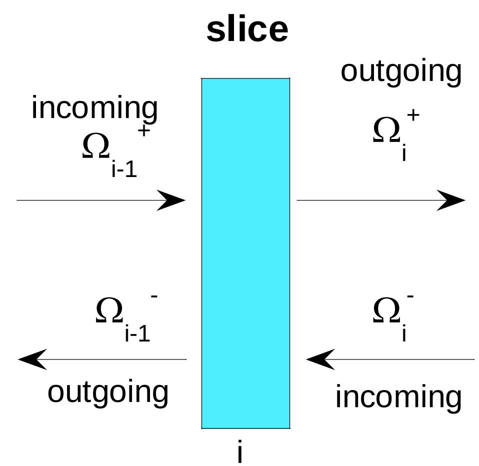
$$\nabla \times E = i\omega H; \nabla \times H = -i\omega\varepsilon(r)E$$

- Maxwell's equations solved in Fourier space in 3-dimensions
- Set up the transfer matrix (T) which is diagonalized to get eigenmodes and eigenfrequencies (Li, Lin PRB 67 046607 (2004))
- Set up scattering matrix S_i for each slice i
- Recursion relations to obtain the scattering matrix for entire structure using scattering matrix for each slice
- Reflection (R), Transmission (T), Absorption (A) for entire structure (A=1-R-T)
- Easily parallelized: each frequency on different processor
- Sub-wavelength hole arrays (Biswas et al PRB **74**, 045107 (2006), R. Biswas, S. Neginhal, C. G. Ding, I. Puscasu, E. Johnson, J. Opt. Soc. of Am. B **24**, 2489 (2007).)
- Advantage over real space method: Thick substrates

$$\left(\frac{\Omega_n^+}{\Omega_0^-}\right) = (S)\left(\frac{\Omega_0^+}{\Omega_n^-}\right)$$

$$\left(\frac{\Omega_i^+}{\Omega_{i-1}^-}\right) = (s^i)\left(\frac{\Omega_{i-1}^+}{\Omega_i^-}\right)$$



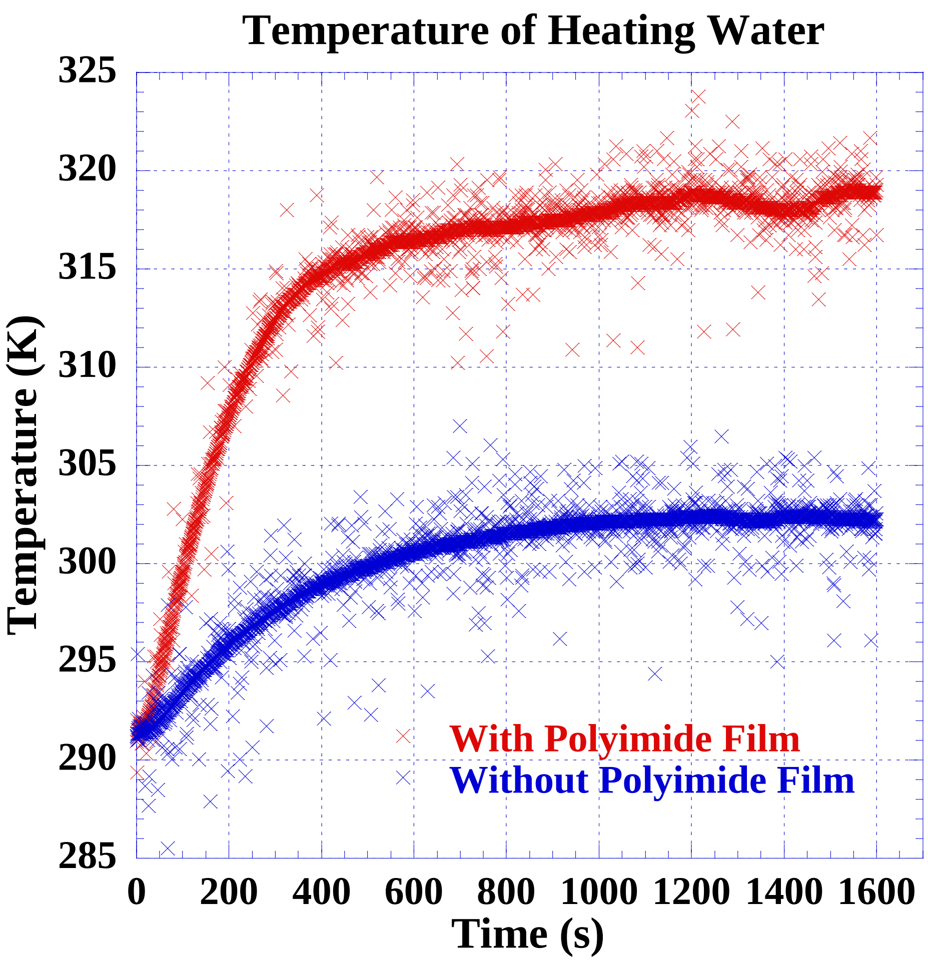


skin depth

$$\delta \approx \sqrt{\frac{2\rho}{\omega\mu}} ......[1]$$

	Chromium	Gold
Electrical Resistivity ρ ($\Omega\cdot$m) (at 20 ℃)	1.25×10^{-7} [2]	2.44×10^{-8} [3]
Wavelength λ (μm)	6	6
Angular Frequency $\omega = 2\pi c/\lambda$ (s^{-1})	$\pi\times10^{14}$	$\pi\times10^{14}$
Vacuum Permeability μ_0 (Hm^{-1})	$4\pi\times10^{-7}$	$4\pi\times10^{-7}$
χ_m	3.5×10^{-6} [4]	-3.4×10^{-5} [5]
Magnetic Permeability $\mu = \mu_0(1+\chi_m) \approx \mu_0$ (Hm^{-1})	$4\pi\times10^{-7}$	$4\pi\times10^{-7}$
Skin Depth δ (μm)	2.516×10^{-2}	1.112×10^{-2}

[1] https://en.wikipedia.org/wiki/Skin_effect
[2] https://en.wikipedia.org/wiki/Chromium
[3] https://en.wikipedia.org/wiki/Electrical_resistivity_and_conductivity
[4] http://www.mit.edu/~6.777/matprops/chromium.htm
[5] http://www.mit.edu/~6.777/matprops/gold.htm



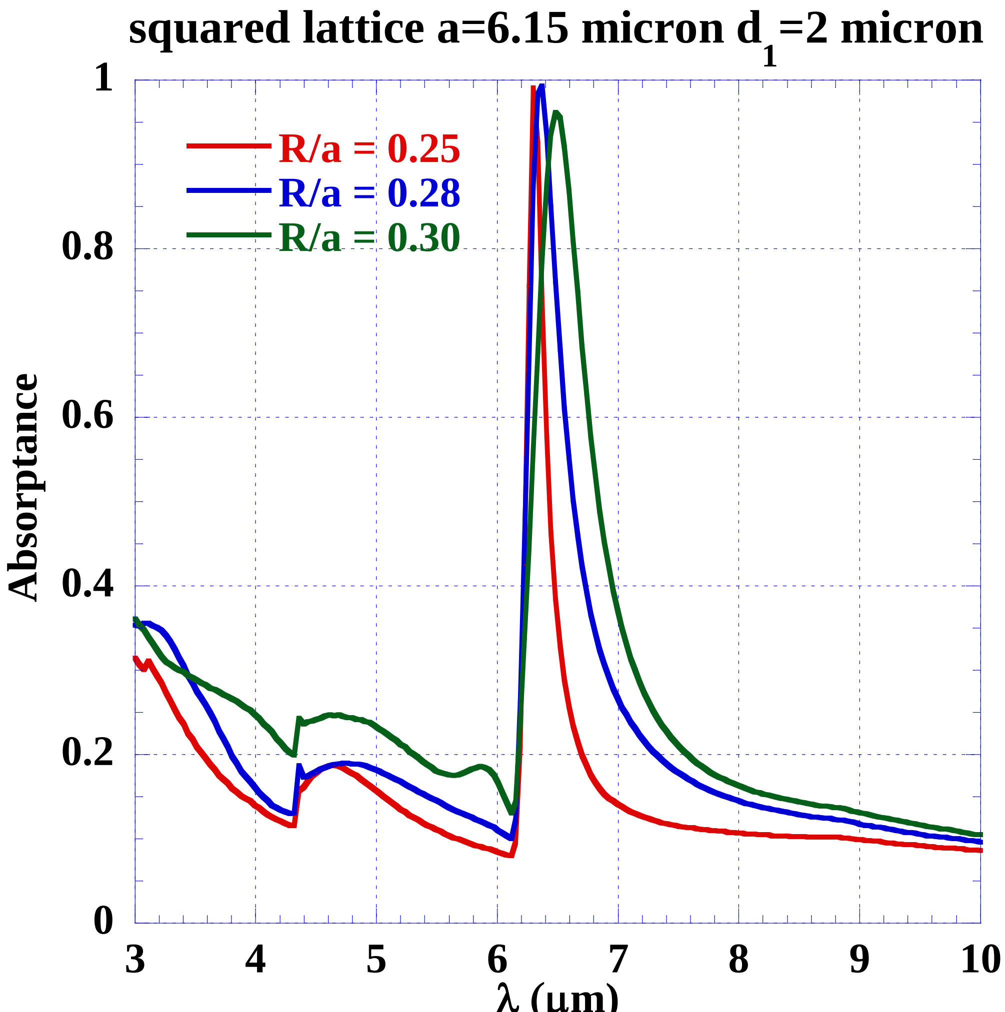
Newton’s law of cooling

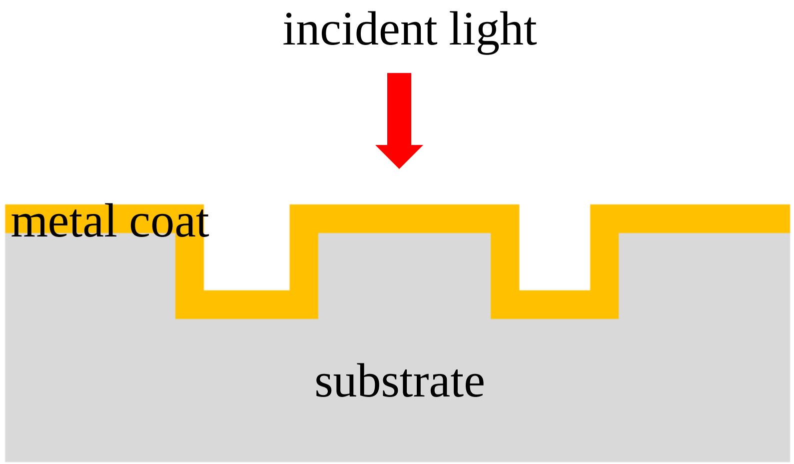
$$\frac{dT}{dt} = -k(T - C) \Rightarrow T = e^{-kt+B} + C$$

$$Q_f = Q_0 - Q = Q_0 - AhT \Rightarrow T_f = \frac{Q_0}{Ah} - e^{-kt+B} - C$$

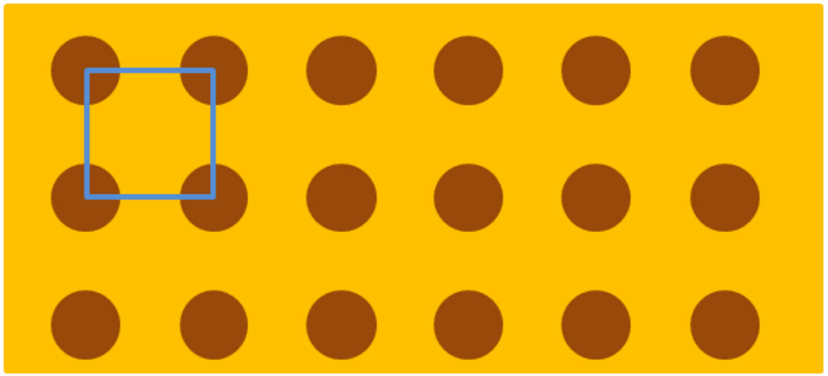
$$t = 0, T_f = C => B$$

The ratio of the radius of hole over the pitch for squared lattice



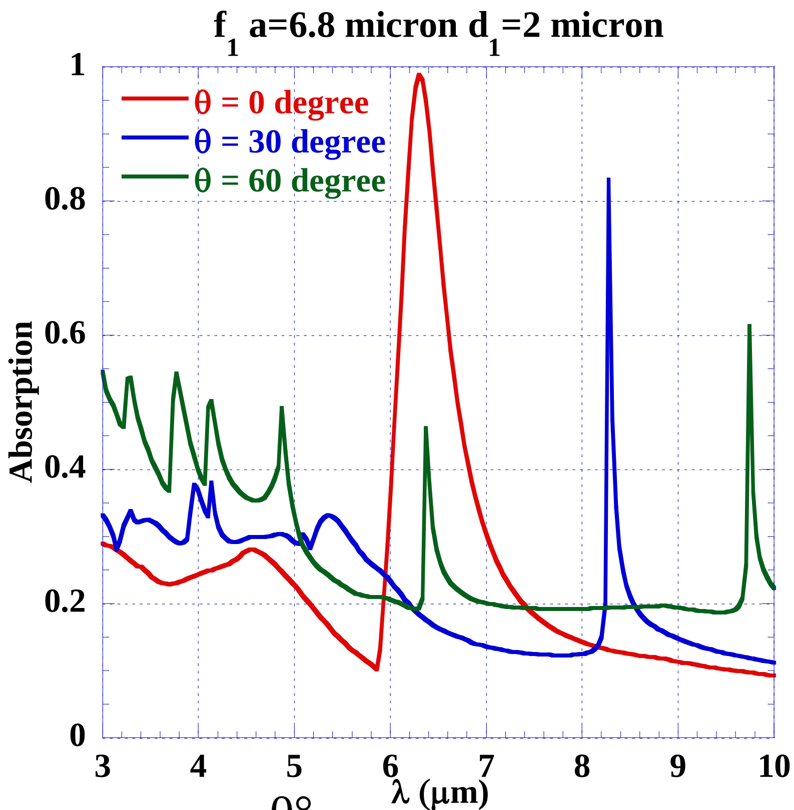


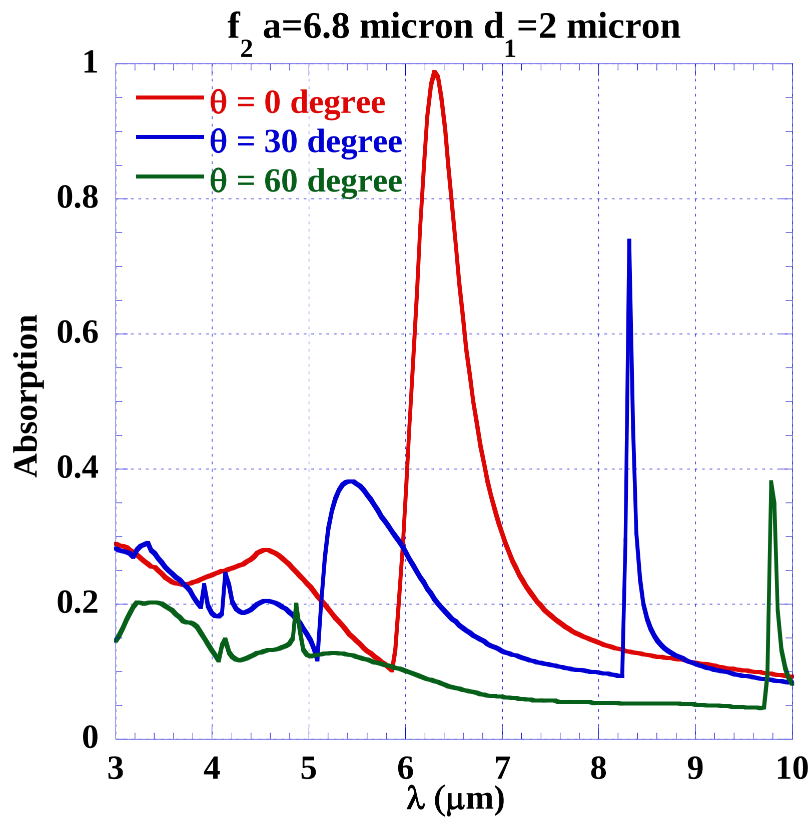
cross sectional view

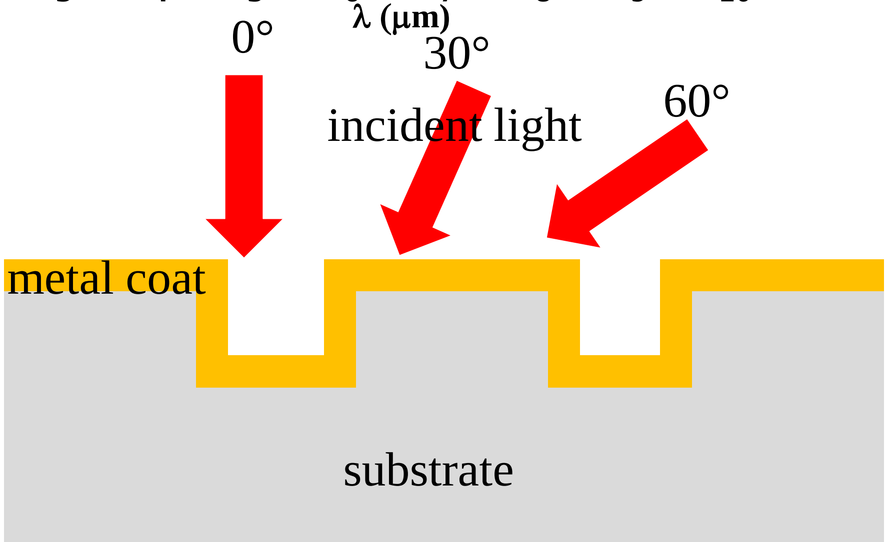


rectangular lattice periodicity

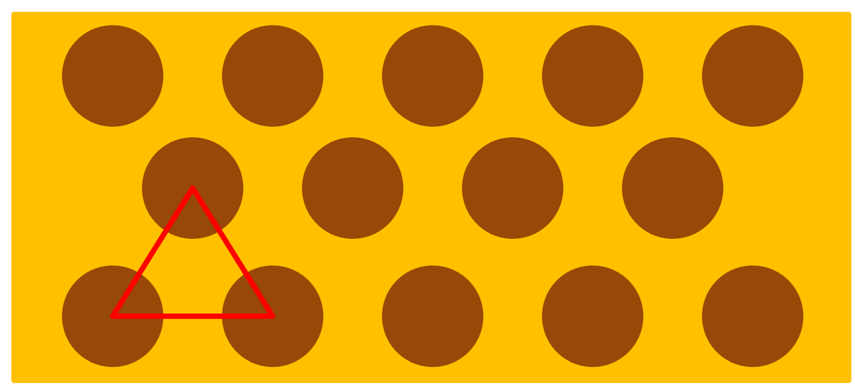
- simulated absorption of the pattern with gold coat.
- depth of the holes changed from 0.5 to 3 microns, the peak shift from 6 to 6.4 microns
- FWHM increased





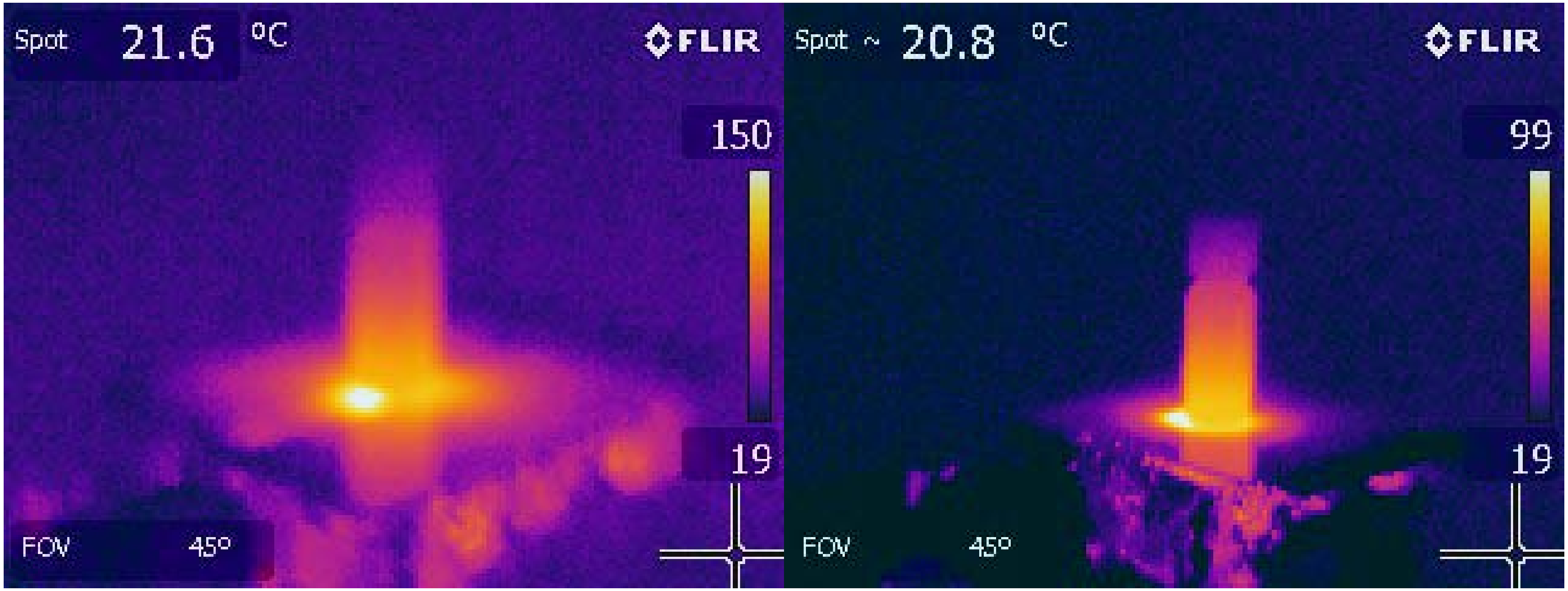


cross sectional view



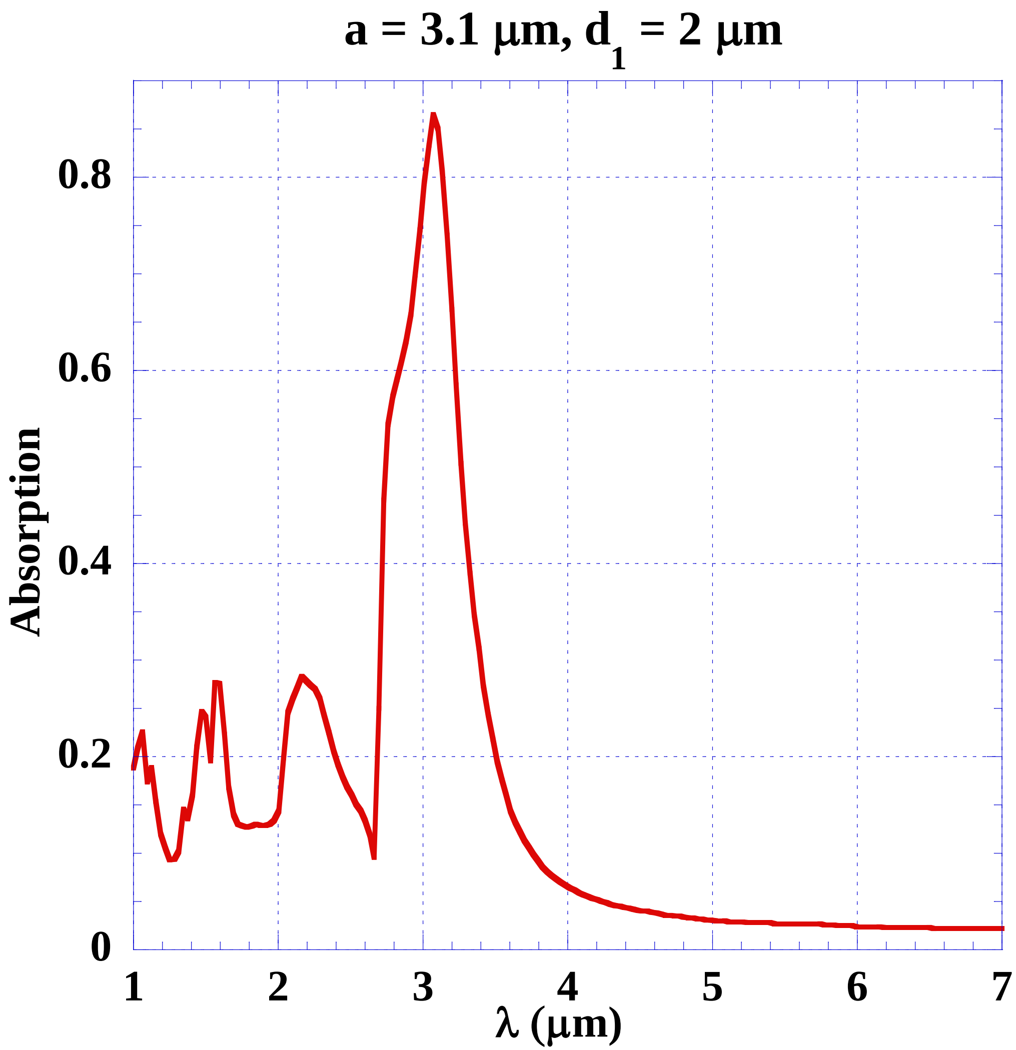
triangular lattice periodicity.

IR images

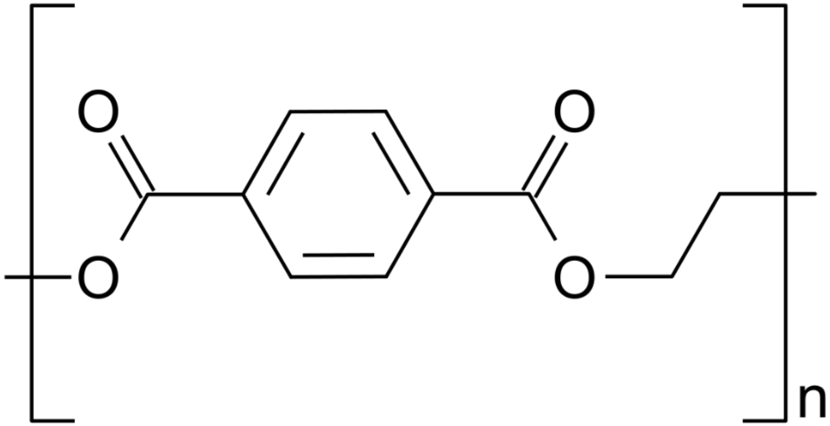


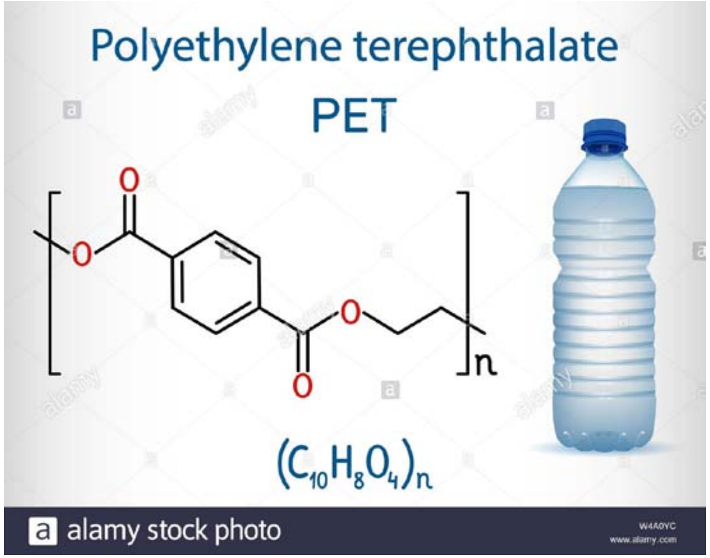
- ➢ The light from a solar simulator was from the bottom of the stage and passed the hole of the stage.
- ➢ The gold coated patterned film with carbon absorber was put above the hole of the stage.
- ➢ A glass bottle was on the patterned film.
- ➢ And the temperature of water inside can reach > 90 °C. Observed *slow* boiling of water

Absorption peak of patterned gold foil at 3.1 microns



- ➢pitch a = 3.1 microns, depth of holes is 2 microns
- ➢the absorption peak is at 3.1 microns




Polyethylene terephthalate
PET
$(C_{10}H_8O_4)_n$
alamy stock photo
W4A0YC
www.alamy.com

Solar thermal

Solar thermal heating of water

__Fig. 1__. Black tube for heating water sold by UKKO, consisting of a glass tube enclosing a thin film heating element.

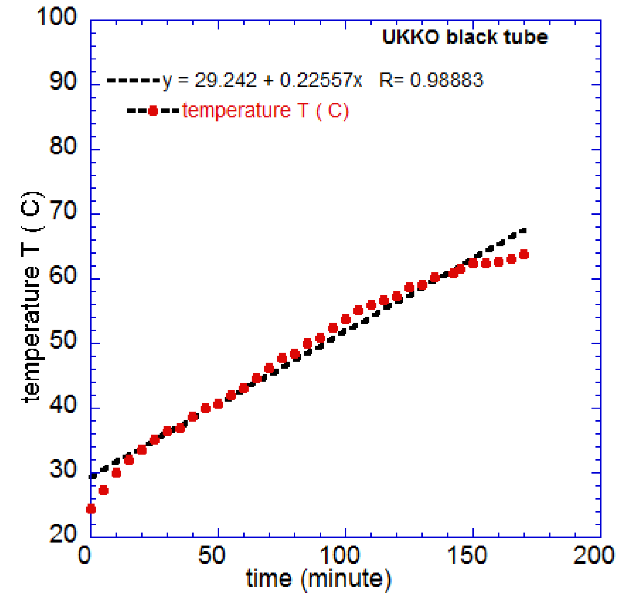
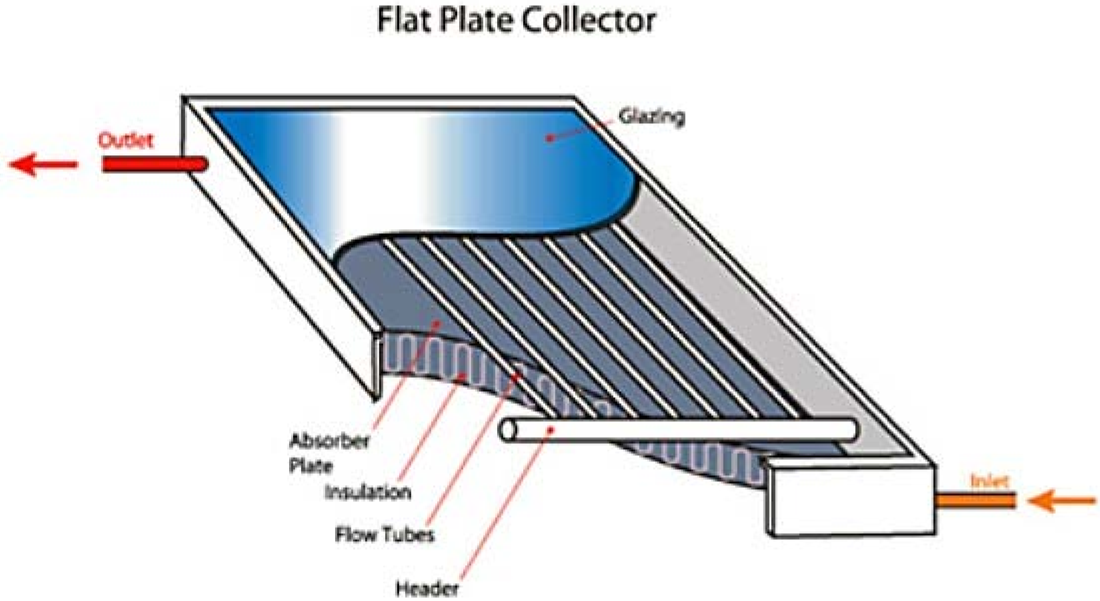


__Fig. 2__ Temperature increase of water in the 'black tube' under full sunlight. The temperature saturates to ~65 ℃ at longer times (> 3 hours).

- Black tube- we put Water in tube in full sunlight
- heated to 60 – 65 C in ~2 hours
- Temperature of water saturates at 60 -65 C even at long times
- Ideal for providing warm water during camping for showers, domestic use
- Can not be used for boiling water or desalination

Solar thermal heaters



Solar thermal water heaters